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The radio–optical correlation in steep-spectrum quasars

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ABSTRACT

Using complete samples of steep-spectrum quasars, we present evidence for a correlation between radio and optical luminosity which is not caused by selection effects, nor caused by an orientation dependence (such as relativistic beaming), nor a by-product of cosmic evolution. We argue that this rules out models of jet formation in which there are no parameters in common with the production of the optical continuum. This is arguably the most direct evidence to date for a close link between accretion on to a black hole and the fuelling of relativistic jets. The correlation also provides a natural explanation for the presence of aligned optical/radio structures in only the most radio-luminous high-redshift galaxies.

Key words: accretion, accretion discs – black hole physics – galaxies: active – galaxies: jets – quasars: general.

1 INTRODUCTION

It is now established that quasars can be divided into two physically distinct classes: radio-loud quasars (RLQs) and radio-quiet quasars (RQQs) (Peacock,, Miller & Longair 1986; Kellermann et al. 1989; Miller, Peacock & Mead 1990; Miller, Rawlings & Saunders 1993; Wilson & Colbert 1995). Relativistic jets are a universal feature of RLQs (e.g. Bridle et al. 1994) and are also probably associated with at least some RQQs (e.g. Miller et al. 1993); the difference between the classes is thus not whether the quasars can form relativistic jets, but is related instead to the fraction of the total power output channelled along them in a bulk kinetic form (see also Rawlings 1994).

It is now also established that at least some radio galaxies harbour obscured quasar nuclei (e.g. Antonucci 1993; Antonucci, Hurt & Kinney 1994; Dey & Spinrad 1996; Ogle et al. 1997). However, the popular notion that the probability of obscuration is a strong function of the angle between the jet axis and the line of sight (e.g. Barthel 1989; Antonucci 1993) due to the ostensible presence of a dusty molecular torus, is still debated, and may apply only to a restricted range of radio luminosity and/or redshift (e.g. Lawrence 1991; Jackson & Rawlings 1997, and references therein). Accepting this orientation-based unification scheme, however, it is possible to combine RLQs and at least some radio galaxies into a single ‘radio-loud’ category, and estimate the power in the photoionizing ultraviolet continuum $Q_{\rm phot}$ (which is hidden in the case of radio galaxies) from the luminosity of the narrow emission lines. By doing this in the 3CRR sample (Laing, Riley & Longair 1983), Rawlings & Saunders (1991) inferred that ‘radio-loud’ objects have bulk powers $Q_{\rm bulk}$ in their jets of the same order as $Q_{\rm phot}$, whereas in the case of RQQs (and their possible obscured counterparts; see Lonsdale, Smith & Lonsdale 1995) the fraction of the power output channelled into jets is $\gtrsim 10^3$ times lower (Miller et al. 1993; Rawlings 1994). The strongly differing fractions seem to be a fundamental difference between radio-loud and radio-quiet active galactic nuclei.

Despite this difference there is some evidence that *within* each class of quasar there is some intrinsic connection between $Q_{\rm bulk}$ and $Q_{\rm phot}$. If one accepts that radio luminosity ($L_{\rm rad}$) and [O III] line luminosity ($L_{\rm [O\,III]}$) are crude indicators of these variables, then the separate, but roughly parallel, loci of the radio-loud and radio-quiet objects in the $L_{\rm rad}$ versus $L_{\rm [O\,III]}$ plane (e.g. Rawlings 1994) hint at a correlation between $Q_{\rm bulk}$ and $Q_{\rm phot}$, whether the jet is in a RLQ (with $Q_{\rm bulk} \sim Q_{\rm phot}$) or a RQQ (with $Q_{\rm bulk} \ll Q_{\rm phot}$). This gives rise to the hope that these relations might constrain models for

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the fuelling of relativistic jets in all types of active galaxies (e.g. Rawlings & Saunders 1991; Falcke, Malkan & Biermann 1995).

However, this is far from being a universally accepted view. In both radio-loud and radio-quiet objects, the correlation between $Q_{\rm bulk}$ and the inferred $Q_{\rm phot}$ can be influenced, or even caused by selection effects in samples used to date, as can the apparently similar magnitudes of $Q_{\rm bulk}$ and $Q_{\rm phot}$ in radio-loud objects. We will discuss this in more detail in Section 3.4.

There are further objections, on physical rather than statistical grounds. For example, Dunlop & Peacock (1993) have suggested that $L_{\rm rad}$–$L_{\rm [O\,III]}$ correlations in radio-loud objects are more plausibly explained by models in which both luminosities are enhanced through interactions between radio jets (and lobes) and a dense environment (see also Baum, Zirbel & O'Dea 1995, and references therein). There are certainly some cases of both radio-loud objects (e.g. Lacy & Rawlings 1994) and radio-quiet objects (e.g. Axon et al. 1989) where at least some of $L_{\rm [O\,III]}$ may be attributable to power supplied by the jet. A key question, therefore, is whether one can find a direct link between $Q_{\rm bulk}$ and $Q_{\rm phot}$, rather than inferring the latter indirectly from $L_{\rm [O\,III]}$.

The optical continua and nuclear emission lines of RLQs are the direct probes of $Q_{\rm phot}$ required. Dunlop & Peacock (1993) cite the lack of a correlation between the optical continuum and radio luminosities of RLQs as an argument in favour of their environmental interpretation of the $L_{\rm rad}$–$L_{\rm [O\,III]}$ correlation. In fact, the existing evidence on the radio–optical correlation for RLQs is mixed (Peacock et al. 1986; Browne & Murphy 1987; Neff, Hutchings & Gower 1989; Miller, Peacock & Mead 1990; Miller et al. 1993 – we will review these contradictory claims in Section 3.4) and, in practice, confused by a number of issues.

First, Peacock et al. (1986) showed that one must not mix RLQs and RQQs, since doing so can produce an apparently universal (but spurious) radio–optical correlation. The authors argued that RLQs have a minimum optical luminosity to explain why 3C quasars are among the brightest optically, and why the RLQs in the optically selected Bright Quasar Survey (Schmidt & Green 1983) are among the most luminous radio sources. This alone would yield a spurious correlation when comparing RLQs with RQQs over a wide optical range. (In fact, our new data rule out this scenario, as we discuss in Section 3.4.)

Secondly, the strong orientation dependence of the optical and radio continua in flat-spectrum, core-dominated RLQs (e.g. Jackson et al. 1989; Baker 1997), can lead to a radio–optical correlation. This follows because radio and optical luminosities can be simultaneously enhanced in these objects by relativistic beaming of synchrotron radiation.

Thirdly, although there are hints of coupled optical–X-ray–radio processes in ostensibly unbeamed RLQs (Browne & Wright 1985; Browne & Murphy 1987), the samples used to date either lack the spectroscopic redshifts which would distinguish radio luminosity dependence from evolution, or have serious and unquantifiable selection biases.

In this paper we present the results of a new study of the radio–optical correlation for quasars in which we have attempted to implement lessons learnt from the studies referenced above. We confined our attention to one of the distinct classes of quasars, the RLQs, since we believe their radio luminosities are a more straightforward indicator of $Q_{\rm bulk}$ (which, with suitable radio data, it is possible to estimate in individual quasars; Rawlings & Saunders 1991; Rawlings 1993). A recent study of the radio–optical correlation in RQQs can be found in Lonsdale et al. (1995). To reduce the effects of relativistic beaming and optical continuum anisotropy, we have also chosen to concentrate on steep-spectrum RLQs (hereafter SSQs), to the exclusion of flat-spectrum, core-dominated quasars. Section 2 outlines the selection and study of our new complete sample of SSQs. To distinguish between $L_{\rm rad}$-dependence and evolution (z-dependence), this sample is combined with two other complete radio-selected samples which together span a wide range in $L_{\rm rad}$ at a given redshift; we also make a comparison with the SSQs in an optically selected sample. In Section 3 we present evidence for a radio–optical correlation, and assess the role of sample selection. In Section 4 we attempt a physical interpretation of the radio–optical correlation, and comment briefly on the implications of this result for studies of radio galaxies. Throughout this paper, we take values of $H_0=100$ km s^{-1} Mpc^{-1}, $\Omega=1$, and a zero cosmological constant.

2 MOLONGLO–APM QUASAR SURVEY

Our new, complete sample of SSQs was drawn initially from the 408-MHz Molonglo Reference Catalogue (MRC) (Large et al. 1981), down to a flux density $S_{408}\geq 0.95$ Jy with a radio spectral index cut-off $\alpha\geq 0.5$ (where $\alpha=-\mathrm{d}\log S_\nu/\mathrm{d}\log\nu$ evaluated near 1 GHz). The survey area is limited to a $\sim$1-sr region in which both UK Schmidt APM (Automated Plate-measuring Machine) data and Texas Catalogue positions (Douglas et al. 1996) were available, bounded roughly by $-35°\lesssim\delta\lesssim 0°$, $21^{\rm h}\lesssim\alpha\lesssim 5^{\rm 5}$. Hence the sample is called the Molonglo/APM Quasar Survey (MAQS) (Serjeant 1996; Maddox et al., in preparation; Serjeant et al., in preparation). Optical identifications were made from the UK Schmidt $b_{\rm J}$ plates, using APM classifications to exclude 'galaxy' identifications brighter than $b_{\rm J}=20.5$. The quasar candidates therefore consisted of all 'stellar' or 'merger' identifications, and all 'galaxy' identifications fainter than $b_{\rm J}=20.5$. Redshifts have been measured (at the Anglo-Australian, William Herschel and Nordic Optical Telescopes) for all quasar candidates to the plate limit of $b_{\rm J}\simeq 22.5$, yielding a complete spectroscopic catalogue of 159 (steep- and flat-spectrum) confirmed quasars. Optical spectra of all quasar candidates (including those rejected for lacking broad optical–UV lines) will appear in a forthcoming paper.

The deep plate limit is very important to this study: only then is the survey likely to detect essentially all the SSQs as far as $z\simeq 3.3$, where the Lyα line leaves the $b_{\rm J}$ band. A recent spectroscopic study of a complete and radio-fainter sample of 7C radio sources (Willott et al. 1997) quantifies this by finding no SSQs optically fainter than the plate limit used for the MAQS (i.e., SSQs with $b_{\rm J}>22.5$ comprise less than 5 per cent of the total population), but that most are fainter than the $B\approx 20$ limit of studies based, for example, on POSS-I.

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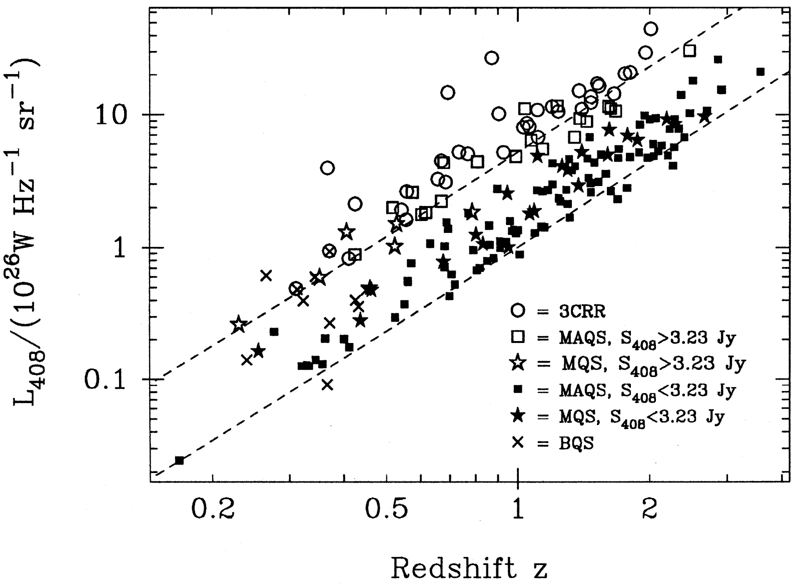

Figure 1. The radio luminosity (L_{408}), redshift (z) plane for SSQs from the MAQS (squares), the MQS (stars), 3CRR (circles) and the BQS (crosses). The brightest 33 per cent (excluding the BQS) have been plotted as open symbols. For 3CRR the 178–750 MHz spectral indices from Laing, Riley & Longair (1983) were used. The loci of sources with $\alpha = 0.85$ and $S_{408} = 0.95$ (MAQS/MQS limit) and 4.94 Jy (3CRR limit) are shown as dashed lines.

We have combined data on our new sample with data on SSQs from the radio-selected 3CRR sample (Laing et al. 1983). In addition, we augment the MAQS sample with SSQs taken from the Molonglo Quasar Sample (MQS) (Baker 1994), also selected from the MRC down to $S_{408} = 0.95$ Jy, and to the b_J plate limit. Finally, we include the SSQs from the optically selected Bright Quasar Survey (BQS) (Schmidt & Green 1983). Fig. 1 shows 408-MHz radio luminosity as a function of redshift (L_{408}, z) for the four samples; the MQS points are plotted in separate symbols in cases where the identification is not shared by the MAQS. Taken together, these four samples provide a wide dispersion in L_{408} at any redshift z, allowing us to distinguish cosmic evolution (z-dependence) from L_{rad}-dependence.

We have split the combined sample into two flux density bins; open symbols are used for the 33 per cent of sources with $S_{408} > 3.23$ Jy, and filled symbols for the remainder. This split was chosen to yield a roughly even fraction in the brighter bin throughout the redshift range. Measured values of radio spectral index, α, were used where available (100 per cent of 3CRR and BQS, 97 per cent of MQS, and 72 per cent of MAQS), and $\alpha = 0.85$ was assumed otherwise. Some of the brighter SSQs, and nearly all the flat-spectrum quasars, should appear in the Parkes catalogue (Wright et al. 1991): for a source on the MAQS radio flux limit the Parkes catalogue should detect all the radio sources with $\alpha \lesssim 0.4$. We are thus confident that flat-spectrum sources have been almost entirely excluded, despite our currently incomplete α information.

3 RESULTS

3.1 The radio–optical correlation

In Fig. 2, optical luminosity is shown as a function of z, again split into bright and faint radio subsamples. In order to calculate the absolute B-magnitude, M_B, we transformed b_J magnitudes to B magnitudes using $B \approx b_J - 0.14$, and adopted typical optical spectral indices of 0.5 (the value derived, for example, from the composite 7C SSQ spectrum by Willott et al. 1997). A more careful treatment of K-corrections was not possible, since a significant fraction of the objects are from the literature, having redshifts but not spectrophotometry. Typical uncertainties in apparent magnitudes are $\sim \pm 0.2$ mag; similar contributions to the absolute photometric errors are made by the uncertainties in the K-corrections. (Error bars are omitted from the plots for clarity.)

Two possible further sources of error are Galactic reddening and emission-line contributions to the b_J flux (intrinsic reddening will be discussed separately below). The Galactic reddening is typically $A_B \simeq 0.2$ mag, and the variations in Galactic reddening are expected to cause an additional relative photometric error of ~ 0.1 mag (de Vaucoleurs & Buta 1983, 1984). This variation is smaller than our typical photometric errors, so we do not correct for it here. The MAQS extends to Galactic latitudes only as low as $|b| = 30°$, so any Galactic reddening is likely to be more significant for 3CRR sources; this would only increase the significance of our results discussed below. Unfortunately, not all the quasars from the literature have published line fluxes, so it is not possible to apply empirical emission-line corrections to the b_J fluxes uniformly over the sample. However, it is well established in RQQ surveys that emission lines make a small contribution to the overall photometric errors (e.g. Schmidt & Green 1983). Since the b_J passband is probably wider than the B selection passband of Schmidt & Green (1983), we might expect the line effects to be even smaller. This is verified in Fig. 3, where we have integrated the composite quasar spectrum of Francis, Hooper & Impey (1993), appropriately redshifted, over the b_J passband. Also plotted is the prediction for an $\alpha_{\mathrm{opt}} = 0.5$ optical power law,

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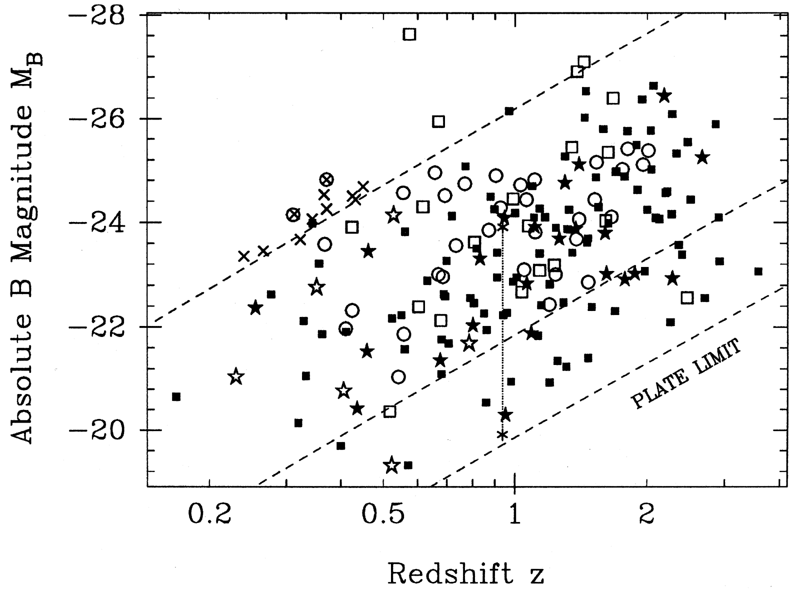

Figure 2. The optical luminosity (M_B), redshift (z) plane (symbols as in Fig. 1). The upper dashed line marks the BQS magnitude limit, and the lower line the MAQS limit; the central line indicates the approximate threshold of reliable star–galaxy separation. The reddened quasar 3C 22 is marked as two asterisks joined by a vertical line (see text).

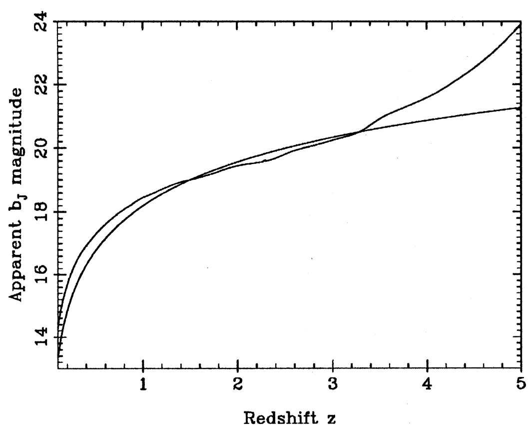

Figure 3. The variation of apparent magnitude with redshift for a quasar of fixed absolute magnitude. The two curves show the variation for a numerical integration of the composite quasar spectrum, and the corresponding variation with a power-law optical quasar continuum (as discussed in the text). The power-law model is the brighter at a redshift of $z=5$. Both models have been normalized to produce the same apparent magnitude at a redshift of 1.5.

which is the continuum slope determined in the composite SSQ spectrum of Willott et al. (1997). The deviations from the power-law model in Fig. 3 are dominated by the slightly atypical (for SSQs) optical spectral index of the Francis et al. (1993) spectrum, except at redshifts $z \gtrsim 3.3$, where Lyα exits the b_J passband. Note the smoothness of the composite quasar curve.

The loci of SSQs at three apparent magnitudes are shown as dashed lines in Fig. 2; the upper line represents the magnitude limit of the BQS ($B=16$), the middle line the $b_J=20.5$ limit above which optically extended objects were removed from the MAQS, and the lower line the $b_J \simeq 22.5$ plate limit of the MAQS and MQS. From Fig. 2, any incompleteness in the MAQS caused by rejecting $b_J<20.5$ optically extended objects is only expected to be present at $z<0.4$. Broad-line radio galaxies from 3CRR are also optically extended on POSS plates, and have not been included. A point-like reddened 3CRR quasar, 3C 22, is plotted in Fig. 2 as two asterisks joined by a line, the lower symbol representing the measured M_B, and the upper representing the magnitude corrected for reddening (see Rawlings et al. 1995).

A clear tendency is seen for the radio-bright quasars at any z to also be brighter optically. This trend cannot be explained solely on the basis of selection effects since, for example, the 3CRR SSQs have no optical magnitude limit, yet are brighter on the whole than the MAQS/MQS quasars.

Comparing in Fig. 2 the SSQs of MAQS/MQS with those of 3CRR (restricting both to the range $0.4<z<2$ to ensure well-matched comparisons), we find a mean apparent magnitude of 18.36 ± 0.20 for sources above 3.23 Jy (open symbols), but 19.22 ± 0.14 for the remainder; the null hypothesis of identical distributions is rejected at $\simeq 99$ per cent confidence by both the Kolmogorov–Smirnov and Mann–Whitney tests. For the combined samples in the restricted redshift range $0.4<z<2$, we find that the optical and radio fluxes are significantly correlated ($\gg 99.9$ per cent confidence using Spearman's correlation coefficient ρ); the same is true of the whole sample (i.e., unrestricted z; Fig. 4). This is the first evidence that the apparent radio–optical correlation is not dominated by a redshift effect.

Fig. 5 shows the L_{408}–M_B correlation implicit in Fig. 2. The correlation in Fig. 5 is significant at $\gg 99.9$ per cent confidence (using Spearman's ρ), with a best-fitting slope of $-2.5 \times (0.6 \pm 0.1)$ (in the $\log_{10} L_{408}$ versus M_B plane) and dispersion of ~ 1.6 optical magnitudes (using 3CRR and MAQS/MQS). However, this slope and dispersion may be

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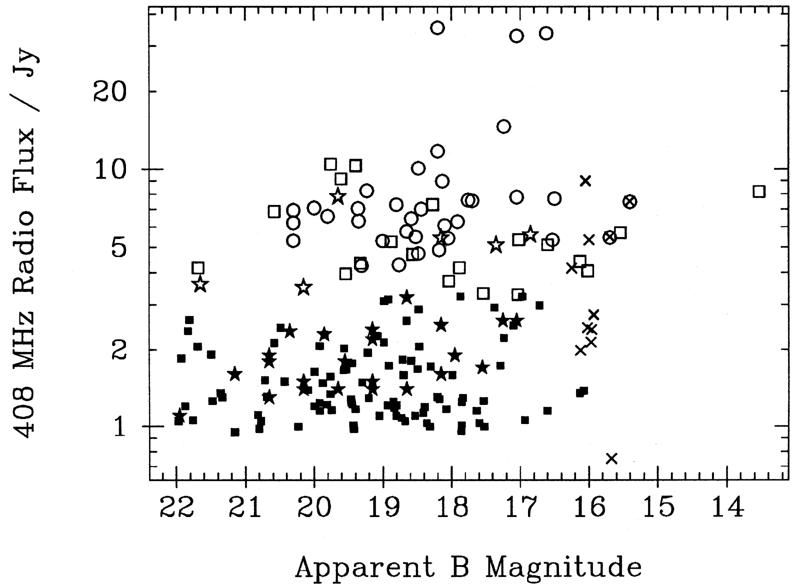

Figure 4. The flux–flux radio–optical relation for SSQs (symbols as in Fig. 1). Note the horizontal offset between the filled (lower) and open (upper) symbols.

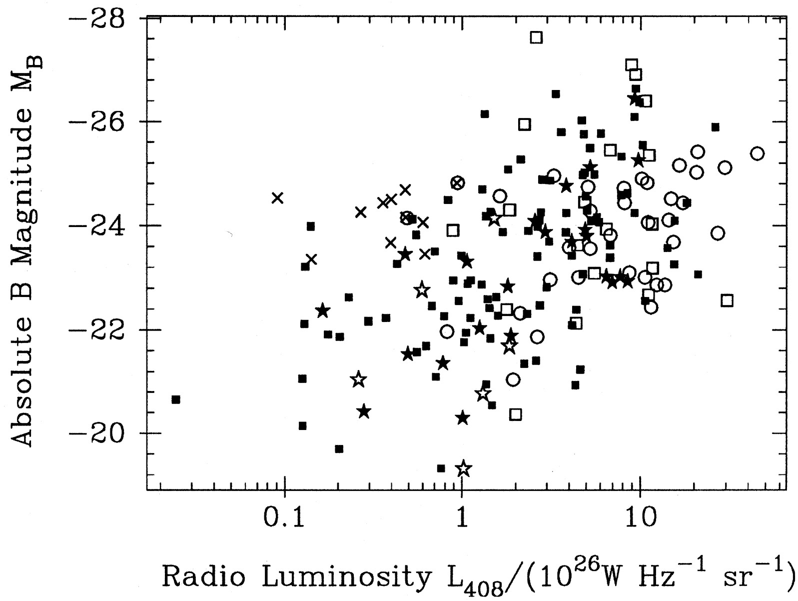

Figure 5. The radio–optical relation for SSQs (symbols as in Fig. 1).

biased estimators of the true values, because the density of points on the plane depends on the weighting imposed by the bivariate (radio–optical) luminosity function (LF), and the sampled comoving volume.

Thus, by comparing the 3CRR and MAQS/MQS samples, we find evidence for the radio–optical correlation which (for the first time) is independent of cosmic evolution. Is the correlation present in any of the samples separately? It might be argued that if a correlation appears only when samples are combined, then it is more suspect than a correlation from a sample in which selection effects are uniform across the sources and where fewer corrections need to be made to intercompare the sources. In fact, the correlation is also present in the MAQS in isolation (to a similar significance level), but it is perhaps instructive to show circumstances in which this type of argument can be misleading. Suppose we had two samples of quasars: the first with $z=1\pm0.1$ and $B=18\pm0.1$, and the second with $z=1\pm0.1$ and $B=22\pm0.1$. It would probably be impossible to demonstrate a radio–optical correlation with either sample in isolation, but once combined the correlation would be far easier to detect.

The L_{408}–M_B correlation in Fig. 5 is supported by the radio properties of the optically faintest SSQs (the band between the lower two dotted lines in Fig. 2). With the exception of reddened quasars like 3C 22, which appears

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well above this band once corrected for reddening (Rawlings et al. 1995), this region includes *no* 3CRR SSQs. It is, however, well populated with MAQS/MQS SSQs. Although reddened examples certainly exist (Baker & Hunstead 1995; Willott et al. 1997), SSQs are typically reddened much less severely than 3C 22 (or are reddened so severely, $A_V \gg 1$, that they will be classified as radio galaxies even on the basis of *K*-band images), since 3C 22 has no clear broad emission lines in the observer-frame optical. This argues strongly against L_{408}-dependent reddening as a cause of the radio–optical relation, an explanation which would in any case require post-shock temperatures finely tuned to the destruction of dust in, and only in, the most luminous radio sources.

This is not to say that reddening does not affect the correlation in any way; we only claim that reddening alone cannot cause it. For example, it remains possible that reddening may affect the scatter in the correlation (see Section 4.2), or that the degree of reddening may be linked to the optical luminosity (e.g., via dust sublimation).

Finally, although our samples have sufficient coverage of the radio–optical–redshift parameter space to demonstrate a radio–optical correlation, they are probably not large enough to address any possible evolution in this correlation. Interestingly, taking the higher redshifts in isolation, the evidence for the correlation is more marginal. However, this may simply be due to a lack of data, and the restricted dynamic range in radio power at high redshifts[1] (see Fig. 1). The same high-redshift radio–optical behaviour is also seen in numerical simulations (discussed below), supporting this interpretation. Nevertheless, it remains possible that the correlation weakens or perhaps fails at high redshifts, implying a different mechanism for jet formation at high ($z \gtrsim 2$) and low ($z \simeq 1$) redshifts (Section 4).

3.2 BQS outliers

The 11 BQS SSQs lie in an atypical region of the correlation. This apparent anomaly is also present in the radio–$L_{[\mathrm{O\,III}]}$ plot (Rawlings 1994), so is unlikely to be (for instance) due to photometric errors in the BQS. There are two points to be made about this feature, which we will support in the next section by numerical simulations. First, there is a selection effect which necessarily overpopulates this region: the BQS, which covers half the sky, selects the rare quasars with the most extreme M_B at any z, favouring the high-M_B side of a radio–optical relation with large intrinsic scatter. In contrast, the deeper MAQS is limited to ~ 1 sr. Secondly, the BQS SSQs are typically ~ 10 times brighter in the radio than the faintest end of the radio LF, $L_{408} \sim 10^{24.5}$ W Hz^{-1} sr^{-1}, where the comoving space density is an order of magnitude higher (Dunlop & Peacock 1990). The lack of BQS SSQs with fainter radio luminosities is difficult to explain without either a radio–optical correlation, or a strongly luminosity-dependent quasar fraction (Lawrence 1991; Jackson & Rawlings 1997; Serjeant et al., in preparation). For the quasar fraction to explain the deficit of low-L_{408} BQS SSQs, the SSQ luminosity function would have to be non-monotonic (i.e., number density must not be a strictly decreasing function of luminosity). There is no evidence for this within the MAQS (Serjeant et al., in preparation), although it is possible that fainter radio samples may find such a luminosity cut-off (e.g. Willott et al. 1997). This leaves the radio–optical correlation as the more plausible explanation. Furthermore, the fact that four of the BQS SSQs are also 3C radio sources (although only two meet the more stringent selection criteria of 3CRR), and are thus among the most luminous radio sources in the sky, is clear evidence for the radio–optical correlation. Nevertheless, in Section 3.3 we also show that the top left-hand corner of Fig. 5 may be less well sampled for SSQs than other regions, so the evidence of a radio–optical correlation in this part of the radio–optical plane is less compelling; a much more convincing demonstration is found to follow from the lack of quasars in the bottom right-hand corner.

[1]Such a selection effect may also be responsible for the apparent tightening of the Q_{phot} versus Q_{bulk} correlation seen at high z in 3CRR (e.g. Rawlings & Saunders 1991).

3.3 Simulated radio–optical relations

As the previous discussion of the BQS outliers illustrates, the passage of flux limits across the radio–optical plane makes a qualitative understanding of the selection effects on the radio–optical relation rather difficult. To clarify the situation, we made numerical simulations of the data. Note that a quantitative comparison of the radio and optical properties of our samples would involve estimating the bivariate radio–optical LF, which will be discussed elsewhere (Serjeant et al., in preparation); here we restrict ourselves to reproducing only the gross properties of our samples.

In Fig. 6 we show the results of Monte Carlo simulations of the MAQS, 3CRR and BQS samples. Points were sampled randomly from the three-dimensional probability distribution defined by the bivariate (radio–optical) LF. In Fig. 6(a), we assume there is no radio–optical correlation, i.e., the bivariate LF is

$$\Phi(L_{408}, M_B, z) \propto \epsilon(M_B, z)\, \beta(L_{408}, z), \tag{1}$$

with the optical LF, ϵ, taken from Boyle et al. (1990), and the radio LF, β, taken from the 'LDE' model of Dunlop & Peacock (1990). We renormalized the Boyle et al. LF to unity, i.e.,

$$\int \epsilon\,(M_B, z)\, \mathrm{d}M_B = 1 \tag{2}$$

at all z; thus we are only using the *shape* of the optical LF, and the cosmic evolution is determined by the radio LF alone. Note that the MAQS SSQs in the (M_B, z) plane of (a) follow the b_J plate limit closely, whereas the 3CRR quasars have no optical flux limit. For simulation (b) (Fig. 6b) we use

$$\Phi(L_{408}, M_B, z) \propto \beta(L_{408}, z)\, \gamma(L_{408}, M_B), \tag{3}$$

with the radio–optical correlation γ modelled as a Gaussian scatter of 1.5 optical magnitudes about the plotted full line, and again adopting the LDE LF β from Dunlop & Peacock (1990). In both simulations we used $\alpha = 0.85$ to convert from 2.7 GHz to 408 MHz.

In both (a) and (b) we sampled 35 points from 3CRR, 118 from MAQS, and 11 from BQS, integrating Φ throughout

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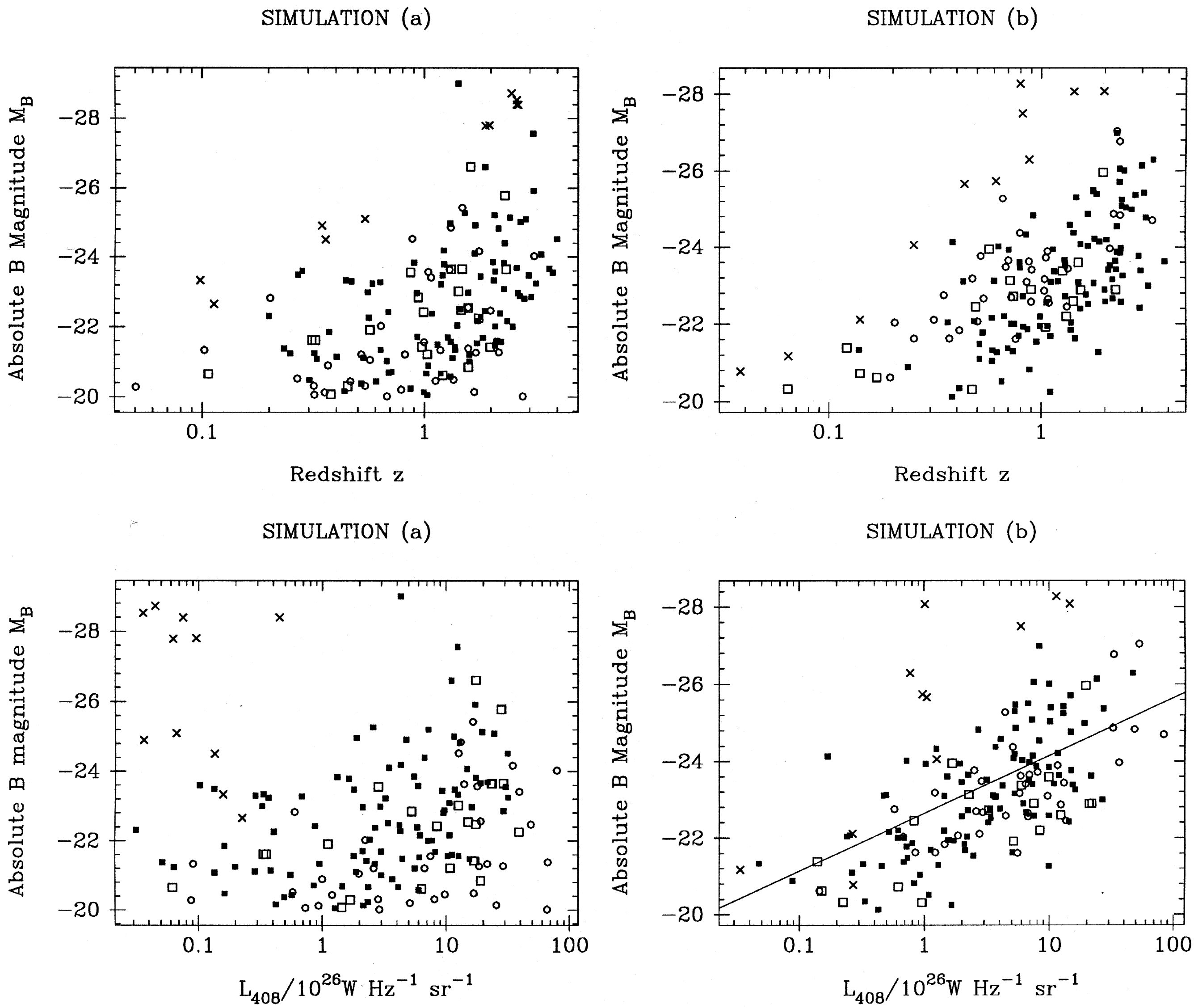

Figure 6. (a) Simulated data without a radio–optical correlation. (b) Simulated data with a radio–optical correlation.

$24.5 < \log_{10}[P/(\mathrm{W\ \ Hz^{-1}\ \ sr^{-1}})] < 29, \quad -20 > M_B > -29$. Simulation (b) reproduces our data qualitatively, including the BQS outliers; the quantitative differences (particularly in the BQS z distributions) are easily explained if the SSQ optical LF $\int \Phi\, \mathrm{d}L_{408}$ evolves differently from the total quasar LF (e.g. La Franca et al. 1994), or if the SSQ radio LF differs from that of radio galaxies (Serjeant et al., in preparation), or perhaps by unknown selection effects in the BQS itself (Goldschmidt et al. 1992). The qualitative agreement was found to be robust to the assumed slope or dispersion in the radio–optical correlation. Simulation (a), however, is grossly inconsistent with our data: a general problem for models without a radio–optical correlation is their inability to explain why SSQs from a bright radio sample (e.g., 3C) are among the brightest optically, and (more marginally) vice versa (e.g., why the BQS contains high-L_{408} SSQs).

An interesting feature of simulation (b) is the lack of evidence for a radio–optical correlation at high redshifts, despite the fact that a correlation is present. In the simulation this is due to the lack of dynamic range in radio power at high redshifts; the correlation has a wide intrinsic dispersion and is not detectable without a wide range in radio power to compensate. A similar behaviour is seen in our 3CRR/MAQS/MQS combined sample at high redshift (Fig. 2), again where the radio power dynamic range is least (Fig. 1). Also, in both our data and in simulation (b), the 3CRR quasars lie slightly on the radio-bright side of the radio–optical correlation. This may be analogous to the BQS outliers (Section 3.2): 3CRR selects the radio-brightest quasars at any z, favouring the high-L_{408} side of a broad radio–optical correlation.

Finally, a very clear (perhaps the clearest) visual demonstration of our correlation is obtained by comparing Fig. 5 with the M_B–L_{408} plane of simulation (a) (Fig. 6a, lower panel). The 3CRR SSQs have no optical flux limit, so in the absence of a correlation there is nothing to prevent them having optical luminosities at the faintest end of the SSQ

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optical LF. This is clearly the case in simulation (a). However, in our data [and in simulation (b)] we find the 3CRR SSQs have optical luminosities lying on roughly the same radio–optical relation as MAQS/MQS. This is obviously difficult to account for unless the radio and optical luminosities are related in some way.

In other words, the lack of SSQs in the bottom right-hand corner of Fig. 5 is real; this area has been well sampled for SSQs. This is clearly highly significant, and we can quantify it as follows. In 3CRR there are 31 SSQs in the range $10^{26} < L_{408} < 10^{27.5}$ W Hz^{-1} sr^{-1}, so if we assign absolute magnitudes uniformly over the range plotted in Fig. 5, we find the probability that the area is empty to be about 10^{-4}. This probability would be much smaller still if we were to use a more realistic optical LF.

In contrast, the top left-hand corner may arguably be less well sampled. The deficit of optically bright MAQS quasars could easily be attributed to the optical LF of SSQs with faint radio luminosities. This leaves the BQS as the only survey which might adequately sample this region. The BQS does indeed lack the radio-faint, optically bright SSQs which would fill this region, in agreement with what we might expect from the radio–optical correlation. However, the lack of these BQS quasars could perhaps be related to the incompleteness worries in the BQS (Goldschmidt et al. 1992). Several authors (e.g. La Franca et al. 1994) have also noted that the total quasar population appears to have a much higher fraction of SSQs locally than at higher redshifts. One suggested explanation of this, which may also help explain the apparent incompleteness in the BQS, is that at such low redshifts the host galaxies may contribute non-negligibly to the total magnitudes. As a result, the BQS (by eye) stellar selection may bias the sample with respect to host galaxy properties at these redshifts in a complicated manner.

3.4 Comparison with previous results

At this point it is worth reviewing previous studies in the light of our correlation, and contrasting the much more problematic selection effects in previous samples. A common problem is the inability to distinguish evolution from luminosity dependence. For example, in Section 1 we discussed the apparent correlation in 3CRR between bulk kinetic jet power $Q_{\rm bulk}$ and the photoionizing radiation power output $Q_{\rm phot}$ as estimated from the narrow-line luminosity $L_{\rm NLR}$ (Rawlings & Saunders 1991). Also, $Q_{\rm bulk}$ and $Q_{\rm phot}$ have similar orders of magnitude in 3CRR, again suggesting a link. However, we will show that the selection criteria of 3CRR could cause both this and the $Q_{\rm bulk}$–$Q_{\rm phot}$ correlation, if 3CRR is taken in isolation.

The $Q_{\rm bulk}$ depends strongly on the total radio luminosity, which in turn correlates strongly with redshift in 3C. This secondary correlation could ultimately lead to spurious relationships within 3C. For example, suppose there is no intrinsic $Q_{\rm bulk}$–$Q_{\rm phot}$ correlation (implying that the correlation in 3CRR is due to some selection effect). Also, make the reasonable assumption that the optical LF of RLQs evolves roughly as strongly as its radio-quiet counterpart. Then the narrow-line luminosity $L_{\rm NLR}$ will correlate strongly with redshift in 3CRR, because $L_{\rm NLR}$ is evolving, and so the $Q_{\rm bulk}$–$Q_{\rm phot}$ correlation in 3CRR would be due entirely to their independent evolution. The apparent similarity of the orders of magnitude of $Q_{\rm bulk}$ and $Q_{\rm phot}$ throughout 3CRR may also be due to this independent evolution, and their apparent similarity would not be preserved in samples of fainter radio luminosity. A similar critique can be made of the radio-quiet $Q_{\rm bulk}$–$Q_{\rm phot}$ relation, although in this case the samples are optically selected rather than radio-flux-limited.[2] However, the presence of a radio–optical correlation in our samples demonstrates for the first time that the Rawlings & Saunders (1991) result is not due to these selection effects, confirming their interpretation, and allows us to predict that the $Q_{\rm bulk}$–$Q_{\rm phot}$ correlation will be preserved in complete samples with fainter limiting radio flux density.

If we assume our observed dispersion in the radio–optical correlation is close to the intrinsic value, then we can also resolve some of the previous contradictory claims on the existence of the correlation.

Peacock et al. (1986) ruled out the null hypothesis that the apparently bimodal distribution of radio-loud and radio-quiet quasars is in fact due to a universal quasar radio–optical correlation (Section 1). Our data can also immediately rule out the alternative model suggested by Miller et al. (1990), that all RLQs have a minimum optical luminosity of $M_B \simeq -23$. Also, on examining their sample selection, it becomes clear why this study failed to detect the correlation. The Miller et al. RLQ sample was wisely restricted to a narrow redshift range, which counters any differential evolution, but unfortunately it was limited to only six SSQs which spanned less than an order of magnitude in both radio and optical luminosities. Given the very broad dispersion apparent in our correlation, it is hardly surprising that they did not detect it. Interestingly, although the Peacock et al. study did not explicitly address the SSQ radio–optical correlation, they noted that several of the quasars in their deeper Parkes subsamples have lower optical luminosities than those in brighter Parkes subsamples. The samples were, however, based in part on compilations from the Véron & Véron (1983) catalogue, and no attempt was made to separate SSQs from flat-spectrum quasars.

Other previous inhomogeneous compilations also gave evidence for an SSQ radio–optical correlation. Neff, Hutchings & Gower (1989) found a clear radio–optical correlation distinct from evolution effects, although their sample was selected from the literature to fill the 2.7-GHz radio luminosity, redshift plane as evenly as possible in the range $1 < z < 2$. While this avoids the tendency towards fainter fluxes inherent in flux-limited samples, it is not clear if this method introduces selection effects of its own, since the parent sample is clearly inhomogeneous. Browne & Murphy (1987) also found a clear radio–optical correlation in lobe-dominated quasars, although their sample was the radio-selected quasars in the Véron & Véron (1983) catalogue with published *Einstein* X-ray observations, which the authors emphasized 'is a very heterogenous sample with all sorts of unknown selection effects'.

On the other hand, Browne & Wright (1985) had the benefit of complete radio-flux-limited samples, but lacked complete specroscopic redshifts. The radio–optical flux–flux correlation present in their fig. 1 could then easily be

[2]Note, though, that the differing $Q_{\rm bulk}/Q_{\rm phot}$ ratios in radio-quiet and radio-loud quasars are robust.

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explained by differing redshift distributions, instead of an intrinsic radio–optical correlation. For instance, one might reasonably expect that fainter samples extend to higher redshifts, so would have correspondingly fainter optical identifications. Such an interpretation is ruled out explicitly in Section 3.1 above.

Miller et al. (1993) presented a study of the radio and optical properties of $z < 0.5$ BQS quasars, although the number of SSQs was again too small to detect our correlation (see also Fig. 5). However, we have also already noted that the completeness of the BQS has been questioned (Goldschmidt et al. 1992).

In summary, the only previous SSQ samples with redshift-independent evidence for a radio–optical correlation were inhomogeneous compilations, so prone to unquantified (and probably unquantifiable) selection effects. The complete SSQ samples, on the other hand, were either too small or too limited in radio or optical dynamic range to detect the correlation we have found.

4 DISCUSSION

4.1 A link between accretion and the fuelling of relativistic jets

We argue here that the SSQ radio–optical correlation (as predicted, for example, in the jet formation models of Ferreira & Pelletier 1995) suggests a close link between the formation of the jets and accretion on to the central black hole. Our discussion is similar to that of Rawlings & Saunders (1991), although it is now with the benefit of more direct evidence for a link between accretion and the fuelling of relativistic jets, and without the selection effect ambiguities.

The narrow range in equivalent widths of broad emission features (e.g. Francis et al. 1993; Miller et al. 1993) and continuum variability studies imply that the bulk of the continuum is produced on subparsec scales, and is most naturally linked to accretion on to a black hole (e.g. Begelman, Blandford & Rees 1984). Therefore the SSQ radio–optical link appears to arise on subparsec scales with the optical light produced by accretion, and with the radio luminosity derived from a centrally formed jet. This confirms the view that the dominant influence on L_{408} is Q, and not the large-scale radio source environment (Rawlings 1993).

It is, of course, possible that the accretion–jet link is not directly causal, since both processes could share a close link with a third parameter. Any correlation of the type shown in Fig. 5 is often dismissed as a 'brighter objects are brighter' effect. However, this scenario necessarily requires the existence of some links to create the scalings, and in the case of the radio–optical correlation where both luminosities are generated by processes within the central parsec, such a link is very likely to be close.

A radio–optical correlation could also be obtained if both M_B and L_{408} for individual quasars evolve separately, but in the same sense, with time. However, if the radio lobes of SSQs are short-lived (i.e., lifetimes $\ll H_0^{-1}$; e.g. Alexander & Leahy 1987), requiring multiple generations of SSQs, then a conspiracy would have to be preserved from $z \sim 3$ to ~ 0.4 despite strongly changing physical environments (e.g. Yee & Green 1987; Ellingson, Yee & Green 1991; Haehnelt & Rees 1993).

The radio–optical correlation supports models in which SSQ jets are fuelled primarily by accretion on to a black hole (e.g. Begelman et al. 1984), perhaps via magnetically driven winds (e.g. Ferreira & Pelletier 1995; Spruit 1996). In general, if any other parameters dominate the jet mechanism (such as disc angular momentum, disc structure, or related magnetic fields), then our correlation implies that they must also control or be controlled by the accretion rate. In particular, this allows us to exclude many classes of models in which SSQ jets are fuelled primarily by black hole spin energy and not accretion energy (Rawlings & Saunders 1990; Begelman et al. 1984). Only if the black hole spin regulates the accretion flow on (possibly) up to kiloparsec scales can such models be sustained; Begelman (1985) presents a model in which he argues that local regulation of the accretion rate may be present.

It is also worth remembering that RQQs follow their own, but clearly different, radio–optical correlation (although it has not yet been shown to be redshift-independent), having far lower jet powers than comparable RLQs (Miller et al. 1993; Lonsdale et al. 1995). Therefore, at least one of the above parameters differs in radio-quiet and radio-loud quasars.

4.2 Scatter in the radio–optical correlation

There are many possible physical interpretations for the broad scatter in our correlation. We will list some of the more obvious candidates here.

First, radio luminosity gives an imprecise measure of the bulk power in the jets (Q_{bulk}) emanating from the central engine, since it also depends on the gaseous environment of the radio source (Ellingson et al. 1991; Rawlings & Saunders 1991); a plot of Q versus M_B may give considerably less scatter than Fig. 5. This would be consistent with the smaller dispersion in the Q–L_{NLR} relation (Rawlings & Saunders 1991) for 3CRR radio sources. Unfortunately, at present we lack the radio data necessary to make the conversion from L_{408} to Q for the MRC and 3CRR SSQs; the compact, steep-spectrum minority may move most in the conversion to Q, because their strong confinement and/or young ages make the L_{408}–Q conversion extremely important. These quasars may also obey a different radio–optical relation if they have significantly fainter or redder continua than the main population (e.g. Baker & Hunstead 1995).

Secondly, reddening of the optical quasar light is very likely contributing to the scatter (Baker & Hunstead 1995; Baker 1996). It may be possible to reduce this cause of scatter by deducing reddening from the optical spectra, but since this typically needs higher quality spectra and/or near-infrared photometry for our MAQS sample, we have not yet been able to investigate this.

Thirdly, optical variability may also increase the observed scatter and may also depend on luminosity. However, the variations are expected to be small for SSQs, about 0.2 mag on average on time-scales of years (Hook et al. 1994). Variability scatter would be reduced by using median magnitudes over a longer time-scale. The intrinsic spread in spectral energy distributions over the observed optical waveband must also contribute to the scatter (e.g. Elvis 1994).

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Fourthly, the sampling of the radio–optical plane is strongly non-uniform, as discussed above, and this may be responsible for some of the apparent dispersion.

Finally, the dispersion could reflect additional dependences on secondary parameters. If this final suggestion is correct, then other observable quantities in SSQs may correlate with their deviation from the best-fitting radio–optical correlation. Such a discovery may provide far stronger observational constraints on the formation of the jets.

4.3 The optical properties of radio galaxies

The radio–optical correlation we have established for SSQs has important implications for the orientation-based unified schemes for active galaxies (e.g. Barthel 1989; Antonucci 1993). The radio–optical relation suggests that amongst objects with a naked quasar nucleus those with the most luminous radio sources are necessarily also highly luminous in the optical. If the compact quasar nucleus is hidden from our direct view, as is now known to be the case in some radio galaxies (e.g. Dey & Spinrad 1996), then in the context of the orientation-based unified schemes the radio–optical relation predicts that a high narrow-line luminosity L_{NLR} is inescapable. The radio–optical relation is then an obvious candidate for the cause of the relation between narrow-line luminosity L_{NLR} and L_{408} for radio sources (Baum & Heckman 1989; Rawlings & Saunders 1991; McCarthy 1993; Rawlings 1993; Jackson & Rawlings 1997).

The SSQ radio–optical relation may also underpin many anomalous properties of the most luminous high-z radio galaxies. For example, most models for the alignment of the radio and optical structure of high-z radio galaxies (e.g. McCarthy 1993) require that roughly constant fractions of Q_{bulk} and M_B are used to supply the different aligned components. If we adopt the view that Q and M_B are closely linked, then as L_{408} drops so must the level of aligned light, whether it is supplied by Q_{bulk} from the jets (e.g. Lacy & Rawlings 1994) or by M_B from the quasar (e.g. by scattering; Tadhunter et al. 1992). The lack of alignments and the low fraction of scattered optical/UV light in less luminous radio sources (Dunlop & Peacock 1993; Cimatti & di Serego Alighieri 1995), independent of redshift, support this prediction.

5 CONCLUSIONS

Using complete samples of SSQs, we have shown that the radio and optical luminosities of SSQs correlate with $\gg 99$ per cent significance, independent of survey selection and cosmic epoch. Such a correlation would naturally explain the observations of aligned optical emission in only the most luminous radio galaxies. Also, we infer that the radio jets of SSQs are regulated by at least one parameter which is shared with the production of the optical continuum; in the accepted standard model for active galactic nuclei this implies a link between accretion and the fuelling of the relativistic jets.

This is not the first observational suggestion of such a link, nor the first claim of a radio–optical correlation. However, it is the first evidence that neither the correlation nor the apparent radio–optical links are caused by selection effects, particularly those inherent in single flux-limited samples such as 3CR.

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